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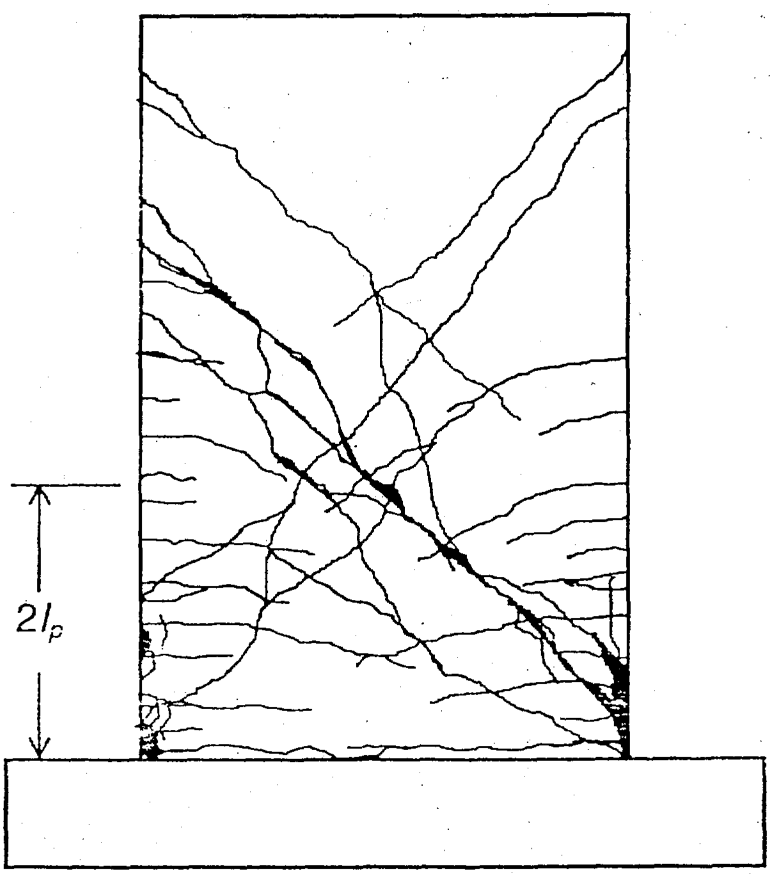
Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings

Technical Resources



FEMA 307

EVALUATION OF EARTHQUAKE DAMAGED CONCRETE AND MASONRY WALL BUILDINGS

Technical Resources

Prepared by:

ATC

The Applied Technology Council

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Prepared for:

The Partnership for Response and Recovery

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Applied Technology Council

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Preface

Following the two damaging California earthquakes in 1989 (Loma Prieta) and 1994 (Northridge), many concrete wall and masonry wall buildings were repaired using federal disaster assistance funding. The repairs were based on inconsistent criteria, giving rise to controversy regarding criteria for the repair of cracked concrete and masonry wall buildings. To help resolve this controversy, the Federal Emergency Management Agency (FEMA) initiated a project on evaluation and repair of earthquake damaged concrete and masonry wall buildings in 1996. The project was conducted through the Partnership for Response and Recovery (PaRR), a joint venture of Dewberry & Davis of Fairfax, Virginia, and Woodward-Clyde Federal Services of Gaithersburg, Maryland. The Applied Technology Council (ATC), under subcontract to PaRR, was responsible for developing technical criteria and procedures (the ATC-43 project).

The ATC-43 project addresses the investigation and evaluation of earthquake damage and discusses policy issues related to the repair and upgrade of earthquake-damaged buildings. The project deals with buildings whose primary lateral-force-resisting systems consist of concrete or masonry bearing walls with flexible or rigid diaphragms, or whose vertical-load-bearing systems consist of concrete or steel frames with concrete or masonry infill panels. The intended audience is design engineers, building owners, building regulatory officials, and government agencies.

The project results are reported in three documents. The FEMA 306 report, *Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings, Basic Procedures Manual,* provides guidance on evaluating damage and analyzing future performance. Included in the document are component damage classification guides, and test and inspection guides. FEMA 307, *Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings, Technical Resources*, contains supplemental information including results from a theoretical analysis of the effects of prior damage on single-degree-of-freedom mathematical models, additional background information on the component guides, and an example of the application of the basic procedures. FEMA 308, *The Repair of Earthquake Damaged Concrete and Masonry Wall Buildings*, discusses the policy issues pertaining to the repair of earthquake damaged buildings and illustrates how the procedures developed for the project can be used to provide a technically sound basis for policy decisions. It also provides guidance for the repair of damaged components.

The project also involved a workshop to provide an opportunity for the user community to review and comment on the proposed evaluation and repair criteria. The workshop, open to the profession at large, was held in Los Angeles on June 13, 1997 and was attended by 75 participants.

The project was conducted under the direction of ATC Senior Consultant Craig Comartin, who served as Co-Principal Investigator and Project Director. Technical and management direction were provided by a Technical Management Committee consisting of Christopher Rojahn (Chair), Craig Comartin (Co-Chair), Daniel Abrams, Mark Doroudian, James Hill, Jack Moehle, Andrew Merovich (ATC Board Representative), and Tim McCormick. The Technical Management Committee created two Issue Working Groups to pursue directed research to document the state of the knowledge in selected key areas: (1) an Analysis Working Group, consisting of Mark Aschheim (Group Leader) and Mete Sozen (Senior Consultant) and (2) a Materials Working Group, consisting of Joe Maffei (Group Leader and Reinforced Concrete Consultant), Greg Kingsley (Reinforced Masonry Consultant), Bret Lizundia (Unreinforced Masonry Consultant), John Mander (Infilled Frame Consultant), Brian Kehoe and other consultants from Wiss, Janney, Elstner and Associates (Tests, Investigations, and Repairs Consultant). A Project Review Panel provided technical overview and guidance. The Panel members were Gregg Borchelt, Gene Corley, Edwin Huston, Richard Klingner, Vilas Mujumdar, Hassan Sassi, Carl Schulze, Daniel Shapiro, James Wight, and Eugene Zeller. Nancy Sauer and Peter Mork provided technical editing and report production services, respectively. Affiliations are provided in the list of project participants.

The Applied Technology Council and the Partnership for Response and Recovery gratefully acknowledge the cooperation and insight provided by the FEMA Technical Monitor, Robert D. Hanson.

Tim McCormick
PaRR Task Manager

Christopher Rojahn
ATC-43 Principal Investigator
ATC Executive Director

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Prologue

This document is one of three to result from the ATC-43 project funded by the Federal Emergency Management Agency (FEMA). The goal of the project is to develop technically sound procedures to evaluate the effects of earthquake damage on buildings with primary lateral-force-resisting systems consisting of concrete or masonry bearing walls or infilled frames. The procedures are based on the knowledge derived from research and experience in engineering practice regarding the performance of these types of buildings and their components. The procedures require thoughtful examination and review prior to implementation. The ATC-43 project team strongly urges individual users to read all of the documents carefully to form an overall understanding of the damage evaluation procedures and repair techniques.

Before this project, formalized procedures for the investigation and evaluation of earthquake-damaged buildings were limited to those intended for immediate use in the field to identify potentially hazardous conditions. ATC-20, *Procedures for Postearthquake Safety Evaluation of Buildings*, and its addendum, ATC-20-2 (ATC, 1989 and 1995) are the definitive documents for this purpose. Both have proven to be extremely useful in practical applications. ATC-20 recognizes and states that in many cases, detailed structural engineering evaluations are required to investigate the implications of earthquake damage and the need for repairs. This project provides a framework and guidance for those engineering evaluations.

What have we learned?

The project team for ATC-43 began its work with a thorough review of available analysis techniques, field observations, test data, and emerging evaluation and design methodologies. The first objective was to understand the effects of damage on future building performance. The main points are summarized below.

- **Component behavior controls global performance.**

  Recently developed guidelines for structural engineering seismic analysis and design techniques focus on building displacement, rather than forces as the primary parameter for the characterization of seismic performance. This approach models the building as an assembly of its individual components. Force-deformation properties (e.g., elastic stiffness, yield point, ductility) control the behavior of wall panels, beams, columns, and other components. The component behavior, in turn, governs the overall displacement of the building and its seismic performance. Thus, the evaluation of the effects of damage on building performance must concentrate on how component properties change as a result of damage.

- **Indicators of damage (e.g., cracking, spalling) are meaningful only in light of the mode of component behavior.**

  Damage affects the behavior of individual components differently. Some exhibit ductile modes of post-elastic behavior, maintaining strength even with large displacements. Others are brittle and lose strength abruptly after small inelastic displacements. The post-elastic behavior of a structural component is a function of material properties, geometric proportions, details of construction, and the combination of demand actions (axial, flexural, shearing, torsional) imposed upon it. As earthquake shaking imposes these actions on components, the components tend to exhibit predominant modes of behavior as damage occurs. For example, if earthquake shaking and its associated inertial forces and frame distortions cause a reinforced concrete wall panel to rotate at each end, statics defines the relationship between the associated bending moments and shear force. The behavior of the panel depends on its strength in flexure relative to that in shear. Cracks and other signs of damage must be interpreted in the context of the mode of component behavior. A one-eighth-inch crack in a wall panel on the verge of brittle shear failure is a very serious condition. The same size crack in a flexurally-controlled panel may be insignificant with regard to future seismic performance. This is, perhaps, the most important finding of the ATC-43 project: the significance of cracks and other signs of damage, with respect to the future performance of a building, depends on the mode of behavior of the components in which the damage is observed.

- **Damage may reveal component behavior that differs from that predicted by evaluation and design methodologies.**

When designing a building or evaluating an undamaged building, engineers rely on theory and their own experience to visualize how earthquakes will affect the structure. The same is true when they evaluate the effects of actual damage after an earthquake, with one important difference. If engineers carefully observe the nature and extent of the signs of the damage, they can greatly enhance their insight into the way the building actually responded to earthquake shaking. Sometimes the actual behavior differs from that predicted using design equations or procedures. This is not really surprising, since design procedures must account conservatively for a wide range of uncertainty in material properties, behavior parameters, and ground shaking characteristics. Ironically, actual damage during an earthquake has the potential for improving the engineer's knowledge of the behavior of the building. When considering the effects of damage on future performance, this knowledge is important.

- **Damage may not significantly affect displacement demand in future larger earthquakes.**

One of the findings of the ATC-43 project is that prior earthquake damage does not affect maximum displacement response in future, larger earthquakes in many instances. At first, this may seem illogical. Observing a building with cracks in its walls after an earthquake and visualizing its future performance in an even larger event, it is natural to assume that it is worse off than if the damage had not occurred. It seems likely that the maximum displacement in the future, larger earthquake would be greater than if it had not been damaged. Extensive nonlinear time-history analyses performed for the project indicated otherwise for many structures. This was particularly true in cases in which significant strength degradation did not occur during the prior, smaller earthquake. Careful examination of the results revealed that maximum displacements in time histories of relatively large earthquakes tended to occur after the loss of stiffness and strength would have taken place even in an undamaged structure. In other words, the damage that occurs in a prior, smaller event would have occurred early in the subsequent, larger event anyway.

What does it mean?

The ATC-43 project team has formulated performance-based procedures for evaluating the effects of damage. These can be used to quantify losses and to develop repair strategies. The application of these procedures has broad implications.

- **Performance-based damage evaluation uses the actual behavior of a building, as evidenced by the observed damage, to identify specific deficiencies.**

The procedures focus on the connection between damage and component behavior and the implications for estimating actual behavior in future earthquakes. This approach has several important benefits. First, it provides a meaningful engineering basis for measuring the effects of damage. It also identifies performance characteristics of the building in its pre-event and damaged states. The observed damage itself is used to calibrate the analysis and to improve the building model. For buildings found to have unacceptable damage, the procedures identify specific deficiencies at a component level, thereby facilitating the development of restoration or upgrade repairs.

- **Performance-based damage evaluation provides an opportunity for better allocation of resources.**

The procedures themselves are technical engineering tools. They do not establish policy or prescribe rules for the investigation and repair of damage. They may enable improvements in both private and public policy, however. In past earthquakes, decisions on what to do about damaged buildings have been hampered by a lack of technical procedures to evaluate the effects of damage and repairs. It has also been difficult to investigate the risks associated with various repair alternatives. The framework provided by performance-based damage evaluation procedures can help to remove some of these roadblocks. In the long run, the procedures may tend to reduce the prevailing focus on the loss caused by damage from its pre-event conditions and to increase the focus on what the damage reveals about future building performance. It makes little sense to implement unnecessary repairs to buildings that would perform relatively well even in a damaged condition. Nor is it wise to neglect buildings in which the component behavior reveals serious hazards regardless of the extent of damage.

- **Engineering judgment and experience are essential to the successful application of the procedures.**

  ATC-20 and its addendum, ATC-20-2, were developed to be used by individuals who might be somewhat less knowledgeable about earthquake building performance than practicing structural engineers. In contrast, the detailed investigation of damage using the performance-based procedures of this document and the companion FEMA 306 report (ATC, 1998a) and FEMA 308 report (ATC, 1998b) must be implemented by an experienced engineer. Although the documents include information in concise formats to facilitate field operations, they must not be interpreted as a "match the pictures" exercise for unqualified observers. Use of these guideline materials requires a thorough understanding of the underlying theory and empirical justifications contained in the documents. Similarly, the use of the simplified direct method to estimate losses has limitations. The decision to use this method and the interpretation of the results must be made by an experienced engineer.

- **The new procedures are different from past damage evaluation techniques and will continue to evolve in the future.**

  The technical basis of the evaluation procedures is essentially that of the emerging performance-based seismic and structural design procedures. These will take some time to be assimilated in the engineering community. The same is true for building officials. Seminars, workshops, and training sessions are required not only to introduce and explain the procedures but also to gather feedback and to improve the overall process. Additionally, future materials-testing and analytical research will enhance the basic framework developed for this project. Current project documents are initial editions to be revised and improved over the years.

In addition to the project team, a Project Review Panel has reviewed the damage evaluation and repair procedures and each of the three project documents. This group of experienced practitioners, researchers, regulators, and materials industry representatives reached a unanimous consensus that the products are technically sound and that they represent the state of knowledge on the evaluation and repair of earthquake-damaged concrete and masonry wall buildings. At the same time, all who contributed to this project acknowledge that the recommendations depart from traditional practices. Owners, design professionals, building officials, researchers, and all others with an interest in the performance of buildings during earthquakes are encouraged to review these documents and to contribute to their continued improvement and enhancement. Use of the documents should provide realistic assessments of the effects of damage and valuable insight into the behavior of structures during earthquakes. In the long run, they hopefully will contribute to sensible private and public policy regarding earthquake-damaged buildings.

1. Introduction

1.1 Purpose And Scope

The purpose of this document is to provide supplemental information for evaluating earthquake damage to buildings with primary lateral-force-resisting systems consisting of concrete and masonry bearing walls and infilled frames. This document includes background and theoretical information to be used in conjunction with the practical evaluation guidelines and criteria given in *FEMA 306: Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings - Basics Procedures Manual* (ATC, 1998a). In both documents, concrete and masonry wall buildings include those with vertical-load-bearing wall panels, with and without intermediate openings. In these documents, shear wall buildings also include those with vertical-load-bearing frames of concrete or steel that incorporate masonry or concrete infill panels to resist horizontal forces. The FEMA 306 procedures for these building types address:

a. The investigation and documentation of damage caused by earthquakes.

b. The classification of the damage to building components, according to mode of structural behavior and severity.

c. The evaluation of the effects of the damage on the performance of the building during future earthquakes.

d. The development of hypothetical measures that would restore the performance to that of the undamaged building.

Supplemental data in this document, FEMA 307, includes the results of the efforts of two issues working groups that focused on the key aspects of adapting and enhancing existing technology for the purposes of the evaluation and repair of earthquake-damaged buildings. The general scope of work for each group is briefly outlined in the following two sections.

1.2 Materials Working Group

The Materials Working Group effort was a part of the overall ATC-43 project. The primary objectives of the Materials Working Group were:

a. To summarize tests and investigative techniques that can be used to document and evaluate existing structural conditions, particularly the effects of earthquake damage, in concrete and masonry wall buildings.

b. To recommend modifications to component force-deformation relationships currently used in nonlinear structural analysis, based on the documented effects of damage similar to that caused by earthquakes.

c. To describe the specification and efficacy of methods for repair of component damage in a coordinated format suitable for inclusion in the final document.

Figure 1-1 illustrates the idealization of the force-deformation relationships from actual structural component hysteretic data for use in nonlinear analysis. The focus of the Materials Working Group was the generalized force-deformation relationship for structural components of concrete and masonry wall buildings, shown in Figure 1-2.

1.2.1 Tests and Investigations

The scope included review of experimental and analytical research reports, technical papers, standards, and manufacturers' specifications. Practical example applications relating to the documentation, measurement, and quantification of the structural condition of concrete and masonry walls and in-fill frame walls were also reviewed. The reviews focused on tests and investigative techniques for identifying and evaluating cracking, crushing, deterioration, strength, and general quality of concrete or masonry and yielding, fracture, deterioration, strength, and location of reinforcing steel. Based on this review of existing information, practical guidelines for appropriate tests and investigative techniques were developed and are included in FEMA 306. These guidelines consist of outline specifications for equipment, materials, and procedures required to execute the tests, as well as criteria for documenting and interpreting the results.

1.2.2 Component Behavior and Modeling

The members of the group reviewed experimental and analytical research reports, technical papers, and practical example applications relating to the force-deformation behavior of concrete and masonry walls and in-fill frame walls. Of particular interest were the effects of damage of varying nature and extent on the hysteretic characteristics of elements and components

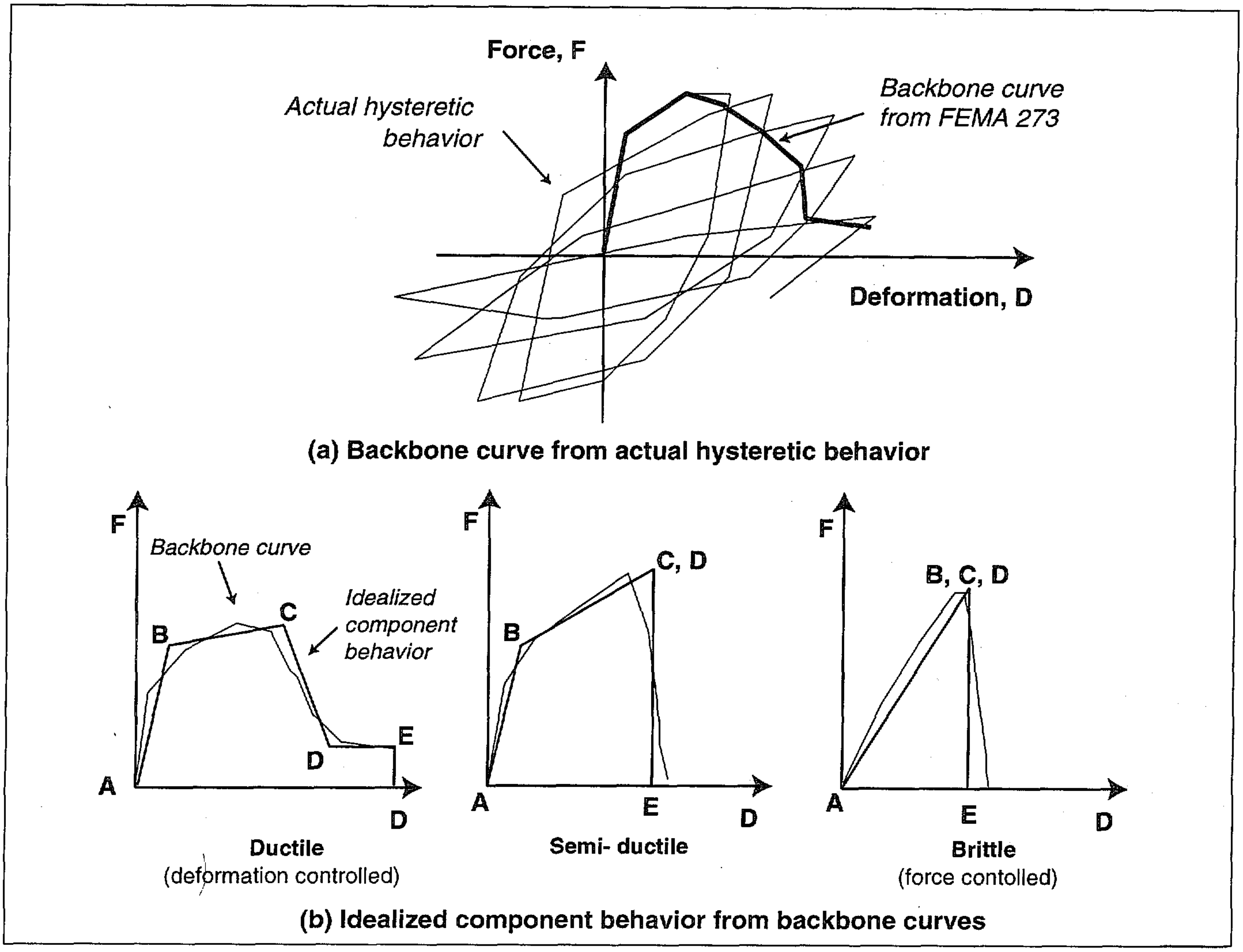


Figure 1-1 ***Component Force-Deformation Relationships***

subject to cyclic lateral loads. The types of damage investigated included cracking and crushing of concrete or masonry and yielding and fracture of reinforcing steel. Components included a wide variety of configurations for vertical-load-bearing and infilled-frame elements. Materials included reinforced concrete, reinforced masonry, and unreinforced masonry.

Based on the review, practical guidelines for identifying and modeling the force-deformation characteristics of damaged components were developed and included in FEMA 306. These consist of modifications (B', C', D', E') to the generalized force-deformation relationships for undamaged components, as shown in Figure 1-2. Supplemental information on these modifications is included in this volume in Chapters 2 (Concrete), 3 (Reinforced Masonry), 4 (Unreinforced Masonry), and 5 (Infilled Frames).

1.2.3 Repair Techniques

The Materials Group also reviewed experimental and analytical research reports, technical papers, standards, manufacturers' specifications, and practical example applications relating to the repair of damage in concrete and masonry walls and infilled-frame walls. The primary interest was the repair of earthquake damage to structural components. The review focused on materials and methods of installation and tests of the effectiveness of repair techniques for cracking, crushing, and deterioration of concrete or masonry and yielding, fracture, and deterioration of reinforcing steel.

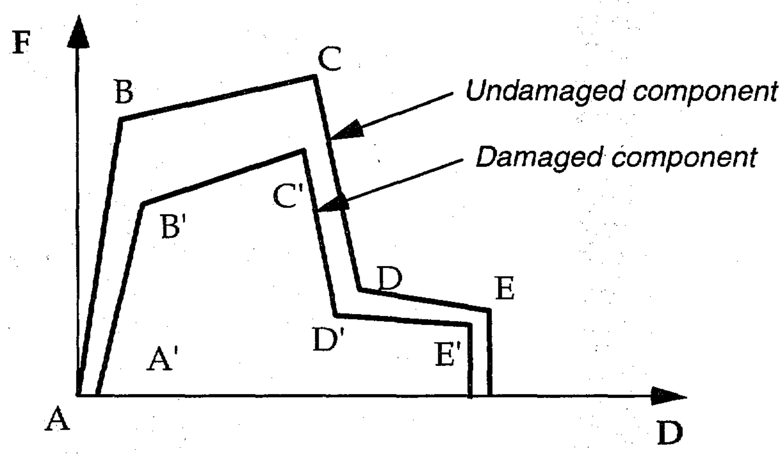


Figure 1-2 ***Generalized Undamaged and Damaged Component Curves***

Based on the review, practical guidelines for damage repair were developed and are contained in *FEMA 308: The Repair of Earthquake Damaged Concrete and Masonry Wall Buildings* (ATC, 1998b). These guidelines consist of outline specifications for equipment, materials, and procedures required to execute the repairs, as well as criteria for quality control and verification of field installations.

1.3 Analysis Working Group

The work of the Analysis Working Group was a sub-project of the overall ATC-43 project. The primary objectives of the group were:

- To determine whether existing structural analysis techniques are capable of capturing the global effects of previous earthquake damage on future seismic performance
- To formulate practical guidance for the use of these analysis techniques in design-oriented evaluation and repair of damaged masonry and concrete wall buildings.

Chapter 6 summarizes the results of the Analysis Working Group efforts. Work consisted primarily of analytical studies of representative single-degree-of-freedom (SDOF) oscillators subjected to a range of earthquake ground motions. The study was formulated so that the following question might be answered (see Figure 1-3): If a building has experienced damage in an earthquake (the *damaging earthquake*), and if that intermediate damage state can be characterized in terms of its effect on the global force-displacement relationship, how will the damage influence global response to a subsequent earthquake (the Performance Earthquake)?

The SDOF oscillators had force-displacement relationships that represent the effects of earthquake damage on the global dynamic response of hypothetical buildings to earthquake ground motions. Types of global force-displacement relationships considered included those shown in Figure 1-4.

The results obtained using existing simplified analyses methods were compared to the time-history results. The group was particularly interested in understanding how nonlinear static analysis methods might be used to represent the findings. Regarding the nonlinear static methods, consideration was given to the applicability of the coefficient method, the capacity-spectrum method, and the secant method of analysis, as summarized in FEMA-273 *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* (ATC, 1997a) and ATC-40 *Seismic Evaluation and Retrofit of Concrete Buildings* (ATC, 1996). The work included a study of the accuracy of the various methods in terms of predicting future performance. The study included an assessment of the

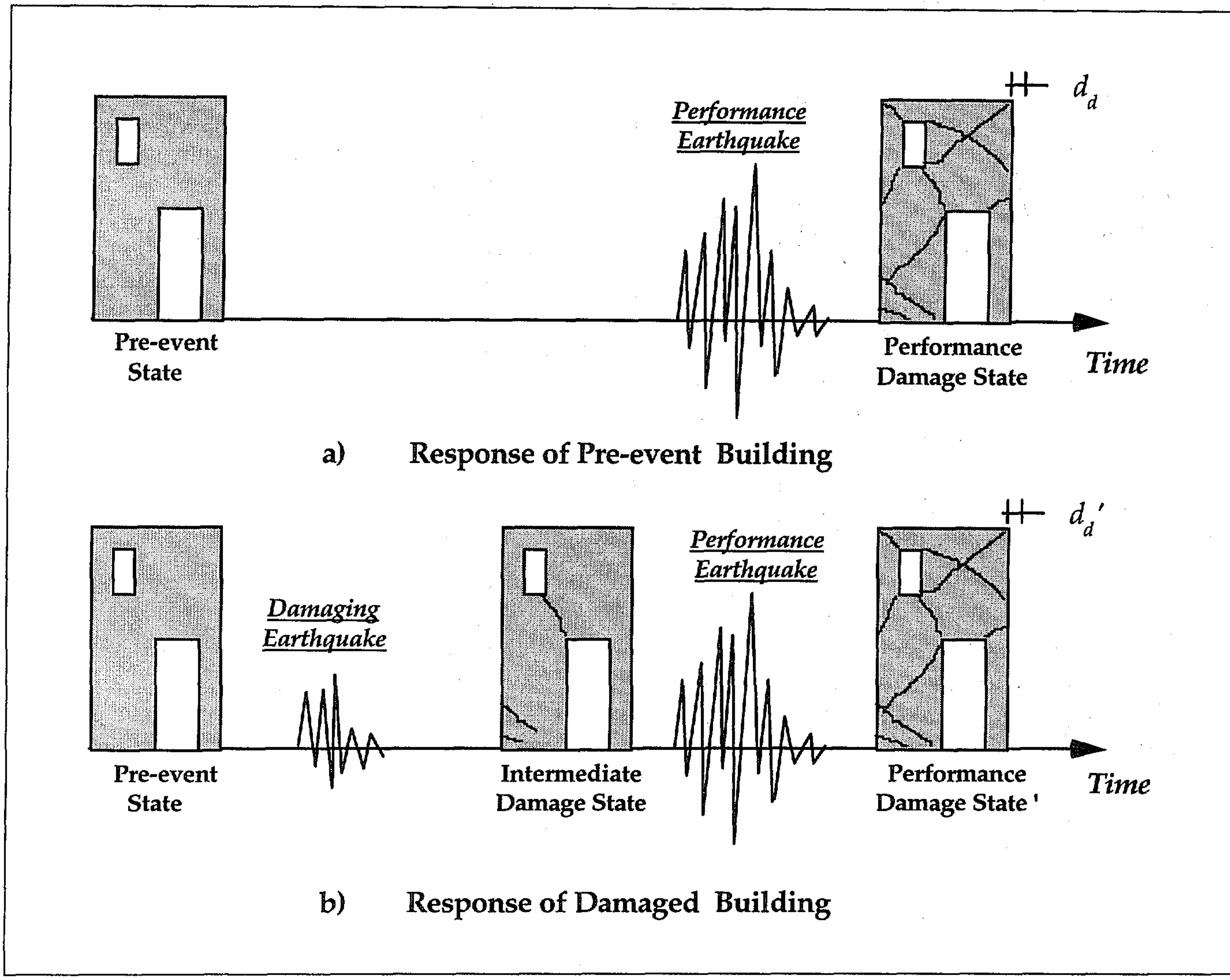


Figure 1-3 *Effect of Damage on Building Response*

sensitivity of the predictions to variations in global load-deformation characteristics and to variations in ground motion characteristics. The results are reflected in the procedures presented in FEMA 306.

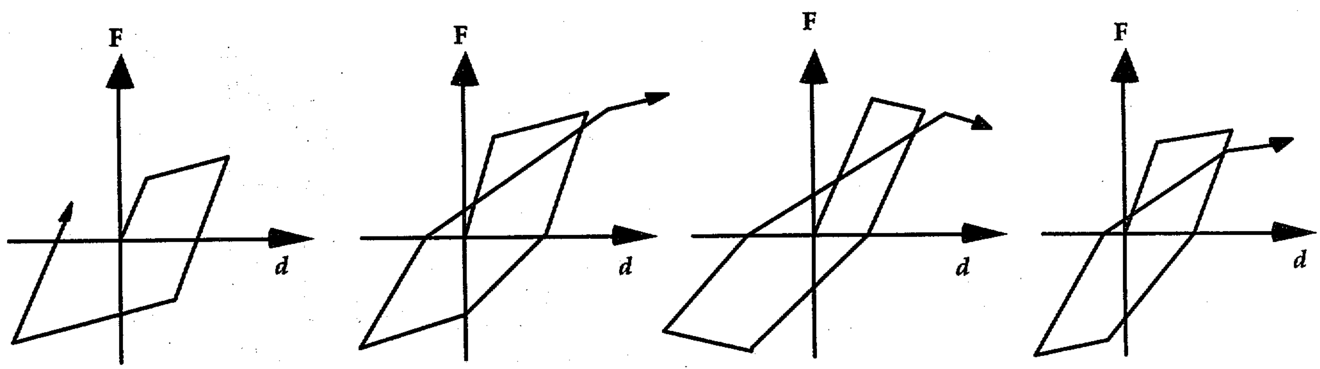
1.4 References

ATC, 1996, *The Seismic Evaluation and Retrofit of Concrete Buildings*, Applied Technology Council, ATC-40 Report, Redwood City, California.

ATC, 1997a, *NEHRP Guidelines for the Seismic Rehabilitation of Buildings*, prepared by the Applied Technology Council (ATC-33 project) for the Building Seismic Safety Council, published by the Federal Emergency Management Agency, Report No. FEMA 273, Washington, D.C.

ATC, 1997b, NEHRP *Commentary on the Guidelines for the Seismic Rehabilitation of Buildings*, prepared by the Applied Technology Council (ATC-33 project) for the Building Seismic Safety Council, published by the Federal Emergency Management Agency, Report No. FEMA 274, Washington, D.C.

ATC, 1998a, *Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings, Basic Procedures Manual*, prepared by the Applied Technology Council (ATC-43 project) for the Partnership for Response and Recovery, published by the Federal



a. Bilinear

b. Stiffness degraded (positive post-yield stiffness)

c. Stiffness Degraded (negative post-yield stiffness)

d. Stiffness and strength degraded

Figure 1-4 Global Load-Displacement Relationships

Emergency Management Agency, Report No. FEMA 306, Washington D.C.

ATC, 1998b, *Repair of Earthquake Damaged Concrete and Masonry Wall Buildings*, prepared by the Applied Technology Council (ATC-43 project) for the Partnership for Response and Recovery, published by the Federal Emergency Management Agency, Report No. FEMA 308, Washington D.C.

2. Reinforced Concrete Components

2.1 Commentary and Discussion

2.1.1 Development of Component Guides and λ Factors

The Component Damage Classification Guides (Component Guides) and component modification factors (λ factors) for reinforced concrete walls were developed based on an extensive review of the research. The main references used are listed in the tabular bibliography of Section 2.3.

2.1.1.1 Identical Test Specimens Subjected to Different Load Histories

As indicated in FEMA 306, the ideal way to establish λ factors would be from structural tests designed specifically for that purpose. Two identical test specimens would be required for each structural component of interest. One specimen would be tested to represent the component in its *post-event* condition subjected to the performance earthquake; the second specimen would be tested to represent the component in its *pre-event* condition subjected to the performance earthquake. The λ values would be derived from the differences in the force-displacement response between the two specimens.

Research to date on reinforced concrete walls does not include test programs as described above. There are only a few tests of identical wall specimens subjected to different loading histories, and typically this is only a comparison of monotonic versus cyclic behavior. For reinforced concrete columns, there are more studies of the effects of load history (El-Bahy et al., 1997; Kawashima and Koyama, 1988) but these studies have not focused on the specific problem of comparing previously damaged components to undamaged components.

2.1.1.2 Interpretation of Individual Tests

In the absence of tests directly designed to develop λ factors, the factors can be inferred from individual cyclic-static tests. This is done by examining the change in force-displacement response from cycle to cycle as displacements are increased. Initial cycles can be considered representative of the damaging earthquake, and subsequent cycles representative of the behavior of an initially damaged component.

The general process of interpreting the test data is outlined in the diagram of Figure 2-1. Each structural test is considered according to the component type and behavior mode represented by the test. At intervals along the load-displacement history of the test the critical damage indicators, such as spalling, cracking, etc., are noted. The damage indicators at each interval are correlated with the displacement ductility reached at that point of the test and with the characteristics of subsequent cycles of the test. From the comparisons of initial and subsequent cycles, λ values are estimated. Critical damage indicators and the associated λ factors are then discretized into different damage severity levels.

The ranges of component displacement ductility, μ_{Δ}, associated with damage severity levels and λ factors and for each Component Guide are given in Table 2-1. The range of ductility values are the result of the differences in test procedures, specimen details, and relative values of coincident loading (shear, moment, axial load). See the remarks column of Table 2-1 for specific factors affecting individual components. Typical force-displacement hysteresis loops from wall tests are given in Section 2.2. A discussion of the relationship between cracking and damage severity for reinforced masonry is given in Section 3.1.2. This discussion is largely applicable to reinforced concrete as well as reinforced masonry.

In estimating the λ values, it was considered that some stiffness and strength degradation would occur in a structural component in the course of the Performance Earthquake, whether or not it was previously subjected to a damaging earthquake. As discussed in FEMA 306, the λ factors refer to the difference in the stiffness, strength, and displacement capacity of the performance earthquake response, between a pre-event component and a post-event component.

2.1.1.3 Accuracy

The λ factors are considered accurate to one significant digit, as presented in the Component Damage Classification Guides. In the case of component types and behavior modes which are not well covered in the research, engineering judgment and comparisons to similar component types or behavior modes were used

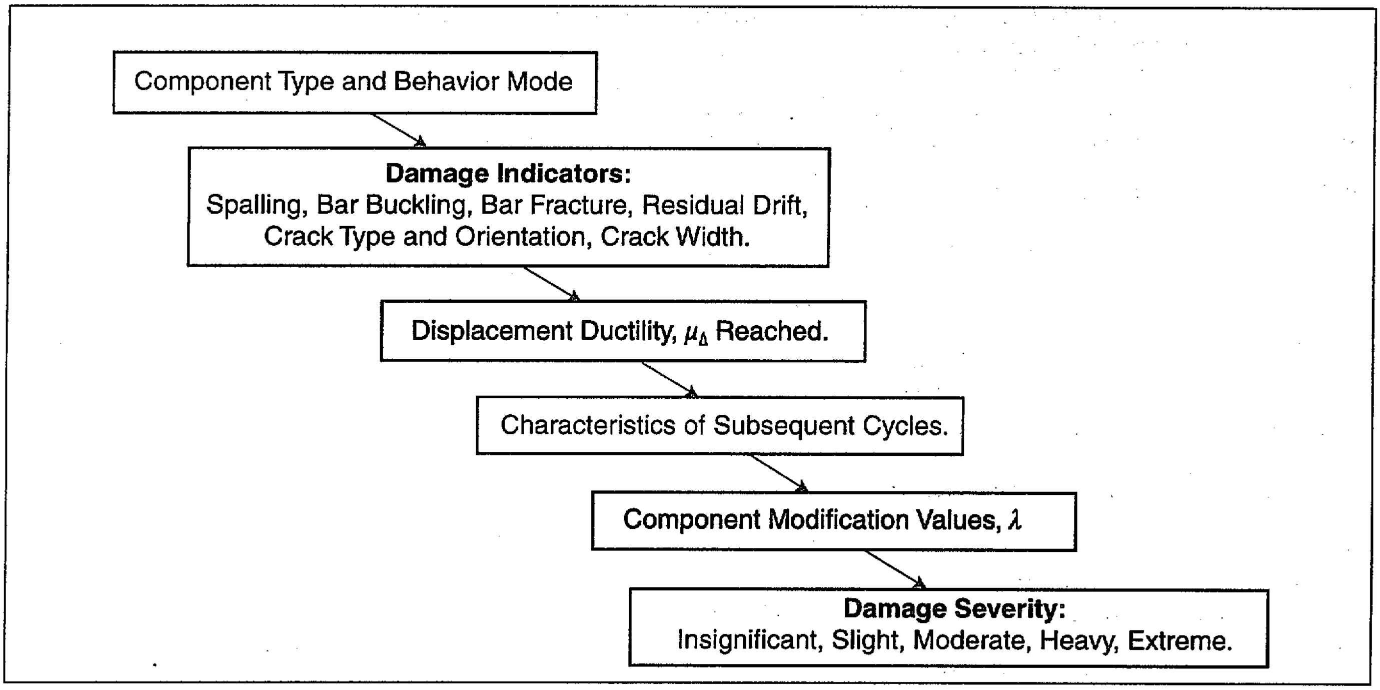


Figure 2-1 ***Diagram of process used to develop component guides and component modification factors.***

to establish λ factors. In cases of uncertainty, the recommended λ factors and severity classifications are designed to be conservative — that is, the factors and classifications may overestimate the effect of damage on future performance.

Only limited research is available from which to infer specific λ_D values. However, a number of tests support the general idea that ultimate displacement capacity can be reduced because of previous damaging cycles. Comparisons of monotonic to cyclic-static wall tests show greater displacement capacities for monotonic loading, and Oesterle et al. (1976) conclude, "structural wall performance under load reversals is a function of load history. The previous level of maximum deformation is critical."

For reinforced concrete columns, Mander et al. (1996) have shown a correlation between strength degradation and cumulative plastic drift. El-Bahy et al, (1997) have shown similar results. This research generally supports the λ_D values recommended for reinforced concrete, which are 0.9 at moderate damage and 0.7 to 0.8 at heavy damage.

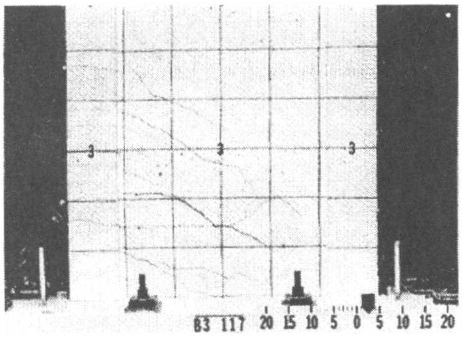
Table 2-1 Ranges of reinforced concrete component displacement ductility, μ_Δ, associated with damage severity levels and λ factors

Component Guide	Damage Severity: Insignif.	Slight	Moderate	Heavy	Remarks on Ductility Ranges
RC1A Ductile Flexural	$\mu_\Delta \le 3$ $\lambda_K = 0.8$ $\lambda_Q = 1.0$ $\lambda_D = 1.0$	$\mu_\Delta \approx 4-8$ $\lambda_K = 0.6$ $\lambda_Q = 1.0$ $\lambda_D = 1.0$	$\mu_\Delta \approx 3-10$ $\lambda_K = 0.5$ $\lambda_Q = 0.8$ $\lambda_D = 0.9$	*Heavy* not used	Slight category will only occur for low axial loads, where concrete does not spall until large ductilities develop
RC1B Flexure/ Diagonal Tension	$\mu_\Delta \le 3$ $\lambda_K = 0.8$ $\lambda_Q = 1.0$ $\lambda_D = 1.0$	*Slight* not used	$\mu_\Delta \approx 2-6$ $\lambda_K = 0.5$ $\lambda_Q = 0.8$ $\lambda_D = 0.9$	$\mu_\Delta \approx 2-8$ $\lambda_K = 0.2$ $\lambda_Q = 0.3$ $\lambda_D = 0.7$	Ductility depends on ratio of flexural to shear strength. Lower ductility indicates behavior similar to preemptive diagonal tension. Higher ductility indicates behavior similar to ductile flexural.
RC1C Flexure/ Web Crushing	$\mu_\Delta \le 3$ See RC1B	*Slight* not used	$\mu_\Delta \approx 2-6$ $\lambda_K = 0.5$ $\lambda_Q = 0.8$ $\lambda_D = 0.9$	$\mu_\Delta \approx 3-8$ $\lambda_K = 0.2$ $\lambda_Q = 0.3$ $\lambda_D = 0.7$	Ductility depends on ratio of flexural to web crushing strength. Lower ductility indicates behavior similar to preemptive web crushing. Higher ductility indicates behavior similar to ductile flexural.
RC1D Flexure/ Sliding Shear	$\mu_\Delta \le 3$ See RC1A	$\mu_\Delta \approx 4-6$ See RC1A	*Moderate* not used	$\mu_\Delta \approx 4-8$ $\lambda_K = 0.4$ $\lambda_Q = 0.5$ $\lambda_D = 0.8$	Ductility depends on ratio of flexural to sliding shear strength.
RC1E Flexure/ Boundary Compression	$\mu_\Delta \le 3$ See RC1A	$\mu_\Delta \approx 4-6$ See RC1A	$\mu_\Delta \approx 3-6$ See RC1A	$\mu_\Delta \approx 4-8$ $\lambda_K = 0.4$ $\lambda_Q = 0.6$ $\lambda_D = 0.7$	Slight category will only occur for lower axial loads, where concrete does not spall until large ductilities develop. Lower ductility relates poorer confinement conditions. Higher ductility indicates behavior similar to ductile flexural
RC2A Ductile Flexural	$\mu_\Delta \le 3$ See RC1A	$\mu_\Delta \approx 4-6$ See RC1A	$\mu_\Delta \approx 3-10$ $\lambda_K = 0.5$ $\lambda_Q = 0.8$ $\lambda_D = 0.9$	*Heavy* not used	See RC1A
RC2H Preemptive Diagonal Shear	$\mu_\Delta \le 1$ $\lambda_K = 0.9$ $\lambda_Q = 1.0$ $\lambda_D = 1.0$	*Slight* not used	$\mu_\Delta \le 1.5$ $\lambda_K = 0.5$ $\lambda_Q = 0.8$ $\lambda_D = 0.9$	$\mu_\Delta \le 2$ $\lambda_K = 0.2$ $\lambda_Q = 0.3$ $\lambda_D = 0.7$	Force controlled behavior associated with low ductility levels.
RC3B Flexure/ Diagonal Tension	$\mu_\Delta \le 3$ See RC1B	*Slight* not used	$\mu_\Delta \approx 2-6$ See RC1B	$\mu_\Delta \approx 2-8$ $\lambda_K = 0.2$ $\lambda_Q = 0.3$ $\lambda_D = 0.7$	See RC1B
RC3D Flexure/ Sliding Shear	$\mu_\Delta \le 3$ See RC1D	$\mu_\Delta \approx 4-6$ See RC1D	*Moderate* not used	$\mu_\Delta \approx 3-8$ $\lambda_K = 0.2$ $\lambda_Q = 0.3$ $\lambda_D = 0.7$	Sliding shear may occur at lower ductility levels that RC1D because of less axial load.

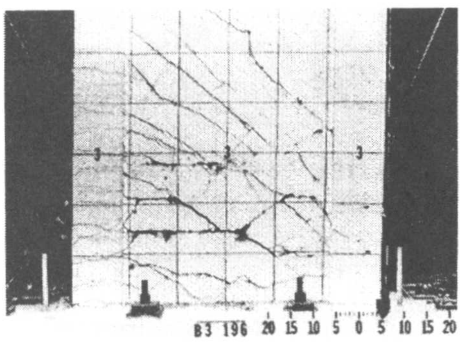
2.2 Typical Force-Displacement Hysteretic Behavior

DAMAGE PATTERNS AND HYSTERETIC RESPONSE

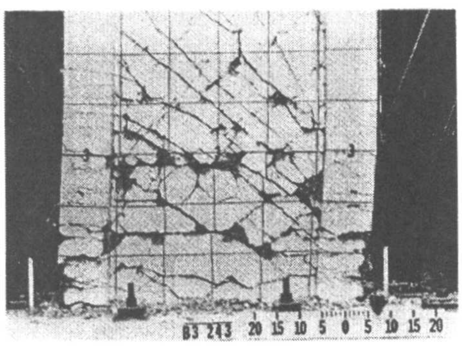
System:	**Reinforced Concrete**	RC1A **Example 1 of 1**
Component Type:	**Isolated Wall or Stronger Wall Pier**	
Predominant Behavior Mode:	**Ductile Flexure**	
Secondary Behavior Mode:	—	
Reference:	Corley, Fioralo, Oesterle (1981), Oesterle et al. (1976), Oesterle et al. (1979)	
Specimen:	B3	



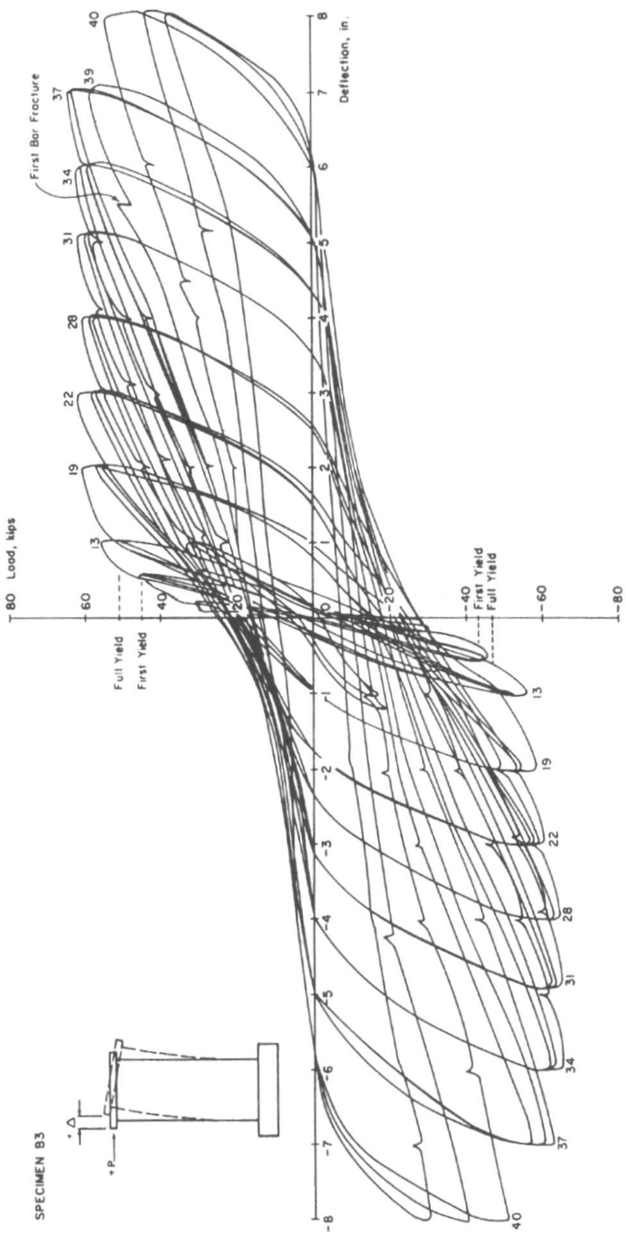
Damage at +3-in. deflection
$\Delta = 3$ in $\quad \Delta/h_w = 0.017 \quad \lambda_Q = 1.0$



Damage at +6-in. deflection
$\Delta = 6$ in $\quad \Delta/h_w = 0.033 \quad \lambda_Q = 1.0$



Damage at +8-in. deflection
$\Delta = 8$ in $\quad \Delta/h_w = 0.044 \quad \lambda_Q = 0.7$

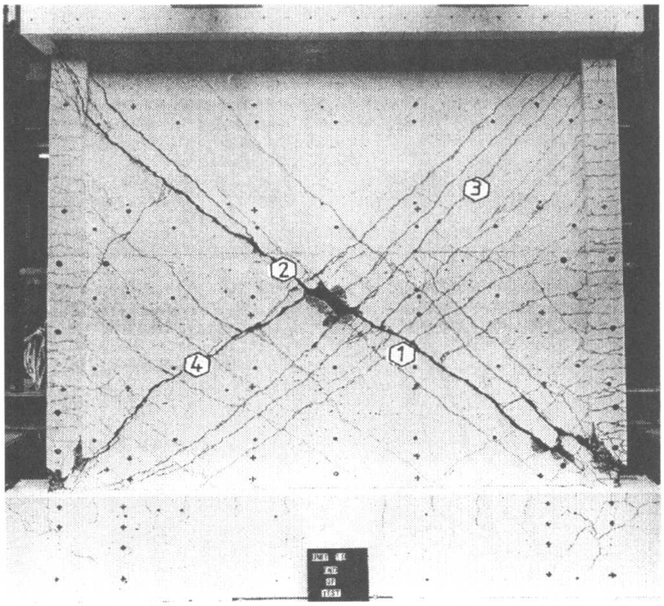


Load versus deflection relationship

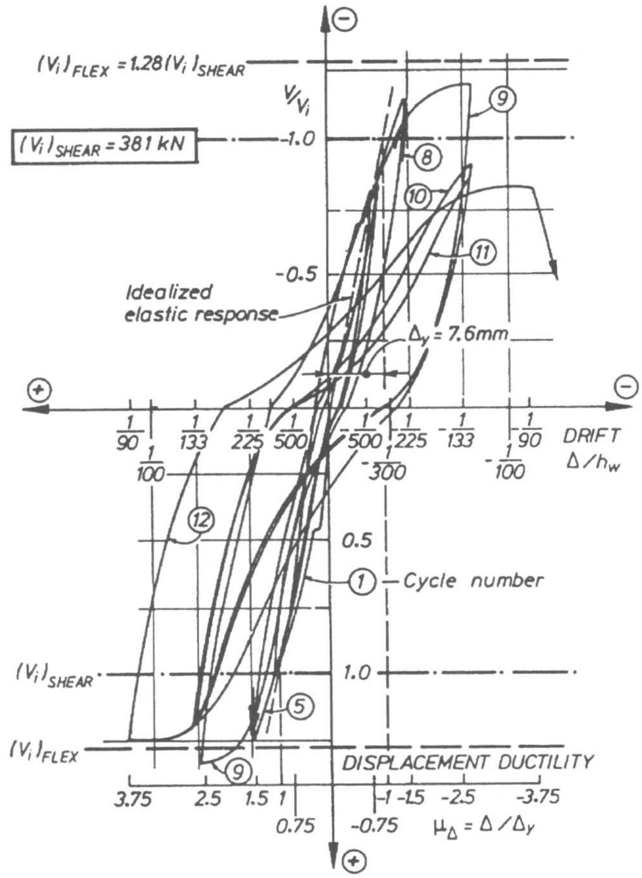
Behavior of Specimen B3

DAMAGE PATTERNS AND HYSTERETIC RESPONSE

System:	**Reinforced Concrete**	RC1B **Example 1 of 2**
Component Type:	**Isolated Wall or Stronger Wall Pier**	
Predominant Behavior Mode:	**Flexure/Diagonal Tension**	
Secondary Behavior Mode:	—	
Reference:	Paulay and Priestley (1992)	
Specimen:	Figure 8.3 of reference	



Failure of a squat wall due to diagonal tension after reversed cyclic loading.



Hysteretic response of a squat wall that eventually failed in shear.